VARIABILITY ANALYSIS IN VACUUM ASSISTED RESIN TRANSFER MOLDING

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ABSTRACT

The vacuum assisted resin transfer molding (VARTM) process is a low-cost, innovative method that is being considered for manufacture of large aircraft-quality components where high mechanical properties and dimensional tolerance are essential. In the present work a rigorous science-based approach is used to study the VARTM processing of high performance complex shape components. A process model, COMPRO©, is used to simulate the cure of panels produced by VARTM. It was found that the presence of the distribution media significantly affects the magnitude of the exotherm particularly for thick panels. For C-shaped laminates, the part distortion was a function of fiber volume fraction distribution and was affected by the presence of the distribution media.

Keywords: VARTM, distortion, process modeling, exotherm, spring-in.

INTRODUCTION

Vacuum assisted resin transfer molding (VARTM) is a low-cost manufacturing process primarily used in the marine industry to make boat hulls and other large structures. More recently, this manufacturing technique was used to make large aircraft components (ref. 1) such as vertical rudders and complex geometry parts found in missile fabrication (ref. 2). Cost reduction is a major benefit of using VARTM over conventional composite processes like autoclave curing. For example, it was estimated

that using VARTM to make a complex component reduced the number of parts from 61 to 1 and eliminated more than 376 fasteners (ref. 2). Consequently, using VARTM resulted in a cost reduction of 75% over a conventional metal design while the component weight was the same and the performance was higher.

One of the critical issues for aerospace applications is the control of the component geometrical dimensions. Components must be assembled and therefore accurate prediction and control of part-to-part variation must be achieved. Dimensional control is achieved during the component processing cycle, thus it is important to have a fundamental understanding of the process. For VARTM, the analysis of the part infiltration process has been the subject of an increasing number of studies (ref. 3-6). Analytical and numerical tools were developed to predict flow front position, part thickness change and local fiber volume fraction. However, the dimensional stability after cure of parts manufactured by VARTM has not been widely addressed. It is well known that the curing process induces residual stresses that may cause part distortions and/or microcracks. These residual stresses are caused by several factors including thermal effects, cure shrinkage and tool-part interaction (ref. 7). Analysis of the spring-in of C-shaped laminates cured by the autoclave process revealed that the net measured spring-in angle was a combination of warpage and corner spring-in. The warpage was found to depend on the tool preparation leading to different tool-part interactions. The corner spring-in was caused by the difference between the longitudinal and transverse coefficients of thermal expansion (CTE) and resin cure shrinkage. The latter is a well known phenomenon when manufacturing anisotropic materials in curved geometries (ref. 8,9). In a previous study (ref. 10), it was found that the selected cure cycle significantly affected the spring-in of C-shaped laminates manufactured by VARTM. A difference in spring-in angle between the resin and vacuum side was observed and was attributed to the asymmetric flow pattern induced during the infiltration process. In a typical VARTM process, the use of a distribution media with a greater permeability than the preform greatly reduces the infiltration time. Consequently, the resin flows in the distribution medium first and then the infiltration process continues through the preform thickness, and thereby leading to potential local fiber volume fraction and thickness variation in the final part. Furthermore, since the resin rich distribution media is cured

with the preform, it is more likely to affect the curing behavior of the part. The resin flow induced fiber volume fraction variation and the presence of the distribution media during cure are two important features specific to the VARTM process that could cause part quality variations.

In this work, the process model COMPRO© (ref. 11) was used to investigate the influence of typical process signatures found in VARTM parts on two key phenomena of composite manufacturing. In the first study, the effect of the distribution media on the temperature profile during cure and particularly the magnitude of the exotherm for thick panels will be investigated. In the second study, the influence of local fiber volume fraction variation and the presence of the distribution media on the distortion of C-shaped laminates are examined.

STUDY I – THICK PANELS EXOTHERM

In this study, the cure of panels with thickness varying from 5 mm to 28 mm thickness was simulated in COMPRO©. The panel material was a multi-axial, non-crimp carbon fiber fabric, SAERTEX®, with a stacking sequence of [-45,90,45,90,0] impregnated with an anhydride cure epoxy resin SI-ZG-5A. The manufacturer's recommended cycle was used. The cure kinetics and viscosity model developed by Grimsley et al. (ref. 12) for SI-ZG-5A were used in the simulations. The panel was assumed to be fully saturated with resin at a fiber volume fraction of 0.45. Thermal properties for the resin and the fiber were taken for a typical epoxy and carbon fiber. The panel and a 5 mm thick aluminum tool were modeled with a one-dimensional column of elements in the thickness direction. A convective heat transfer boundary condition (30 $W/m^2{}^\circ C$ heat transfer coefficient) was assumed on the top and bottom surfaces of the tool-part assembly. The heat transfer and resin cure kinetics were modeled and while resin flow during cure was neglected. The Plastinet® distribution media was modeled as a 3 mm layer of nylon/SI-ZG-5A composite with a fiber volume fraction of 0.23.

Figure 1 shows the temperature profile for a 28 mm thickness panel predicted by the model. The exotherm is very well defined at about 170 seconds and a clear non-uniform

temperature distribution through the thickness is observed. Figure 2 shows the temperature profile trough the thickness at the exotherm temperature predicted by the model. The temperature profile for the case where the distribution media was included in the model agrees well with the thermocouple reading measured during the actual cure of a 28 mm thick panel. However, the model for which the media was not included significantly under-predicts the magnitude of the exotherm. Figure 2 also shows that the presence of the resin rich distribution media affects the shape of the temperature profile leading to an unsymmetric profile. The maximum temperature is therefore shifted to the top section of the laminate instead of the traditional mid-plane. It is clear that neglecting the distribution media during cure simulation can lead to a significant error on the prediction of the temperature variation in the part during cure. This error is more important when modeling thick panels as shown in Figure 3. The error in the prediction of the exothermic temperature is relatively small for thin panels (1.4 °C for 5 mm), but increases rapidly with panel thickness (16.4 °C for 28 mm).

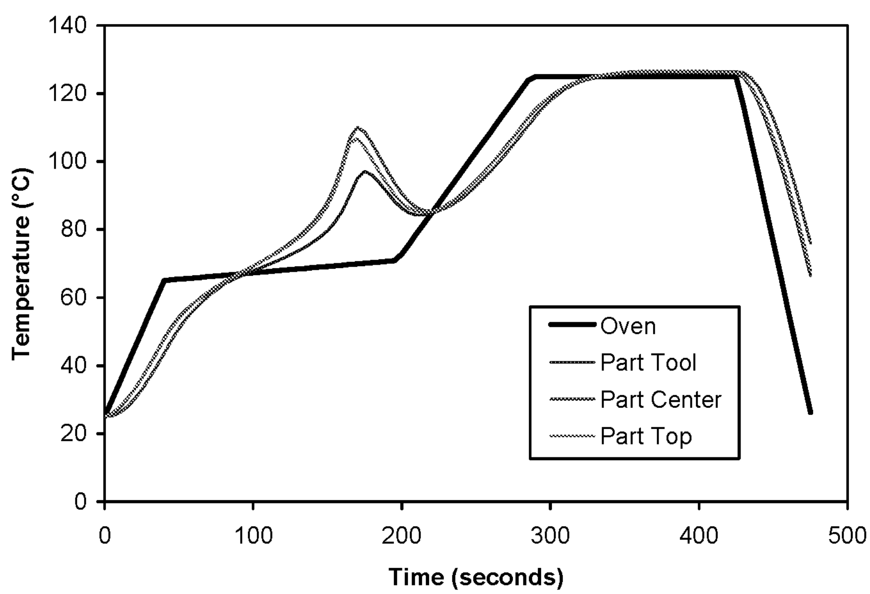


Figure 1 Temperature profile showing the exotherm for a 28mm thick flat panel.

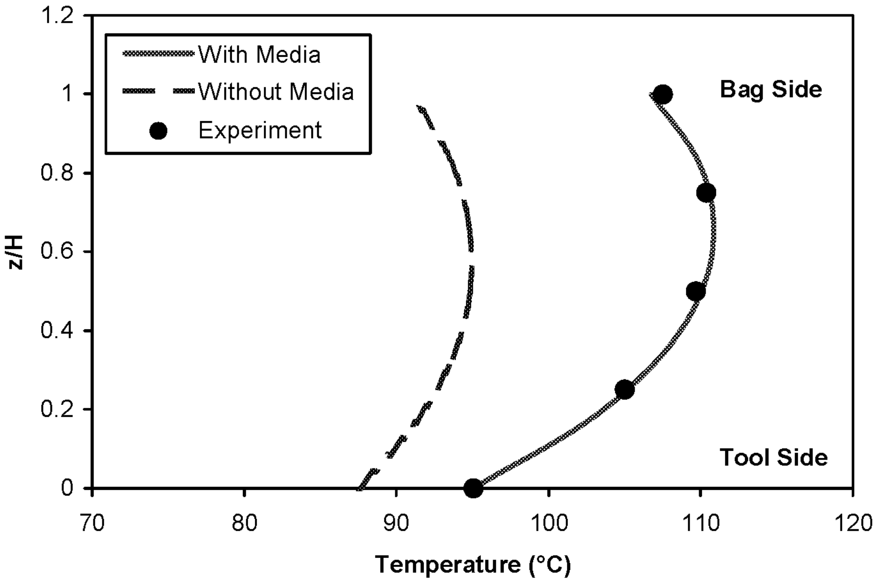


Figure 2 Effect of the presence of the distribution media on panel temperature profile during the exotherm.

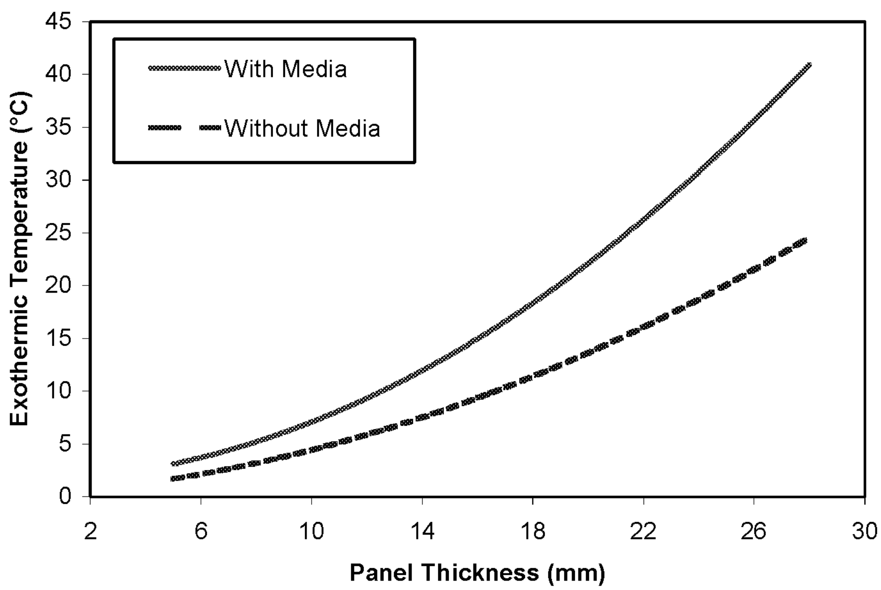
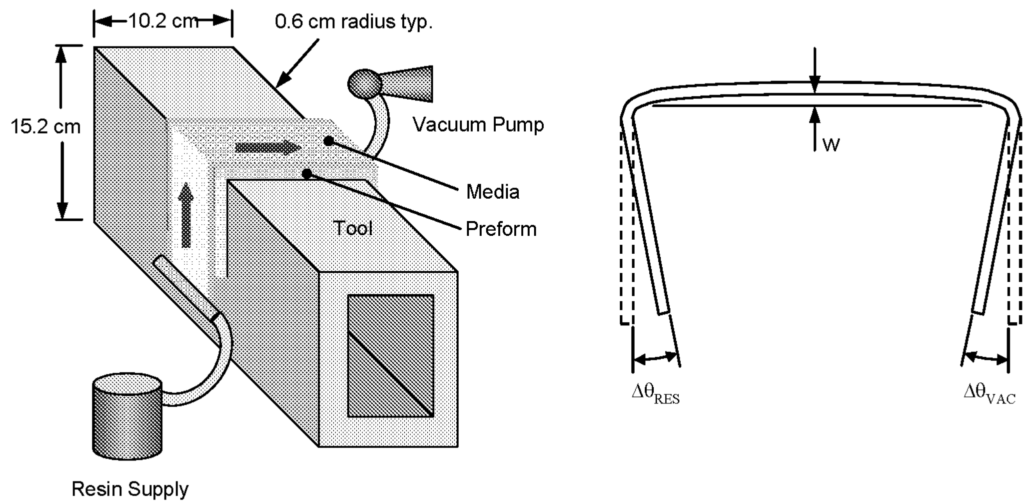


Figure 3 Magnitude of exothermic temperature as function of panel thickness and presence of the distribution media.

STUDY II – C-SHAPED LAMINATES DISTORTION

In this study, the cure of C-shaped SAERTEX®/SI-ZG-5A laminates was simulated. The laminates contained two stacks of fabric resulting in a [45,-45,0,90,0,-45,45]s ply sequence. A 12.5 cm thick aluminum rectangular profile was used as a rigid tool surface (Figure 4a). The tool outside dimensions was 10.2 cm x 15.0 cm with a radius of 0.6 cm on the corners. The high-permeability distribution media consisted of two 7.6 cm x 26.7 cm layers of Plastinet® nylon mesh. A 1.3 cm gap between the edge of the media and the preform side edges and end (vacuum) edge was maintained. Figure 5 shows the finite-element mesh used for the laminate, tool and distribution media. A shear layer was added between the tool and the laminate elements to account for the tool-part interaction. The resin properties were obtained from cure kinetic and viscosity characterization tests (ref. 12). The laminate distortion was measured by the spring-in angles ($\Delta\theta_{RES}$ and $\Delta\theta_{VAC}$) and by the web warpage (w) as illustrated on Figure 4b. The parameters considered were the presence of the distribution media, the fiber volume fraction distribution and its value. For the effect of the presence of the distribution media, a second model was built including only the tool, the shear layer and the laminate elements. To induce a fiber volume fraction distribution in the laminate, a pressure gradient was applied to the perform by prescribing a pressure corresponding to the atmospheric pressure (101 KPa) on the resin side and to the vacuum pressure (1 KPa) on the vacuum side as depicted on Figure 5.

Table 1 presents the part distortion results for the different cases studied. Figure 6 shows a typical deformed shape of the laminate after tool removal. The displacements were magnified to visualize the spring-in angle induced during cure. From Table 1, resin flow causes a fiber volume fraction gradient in the laminate which leads to higher spring-in on the resin side compared to the vacuum side. Also, a higher fiber volume fraction leads to less part distortion. Finally, the presence of the distribution media slightly increases the part distortion as the spring-in angle increases from 0.01 to 0.04° and the warpage changes sign from -0.126 to -0.154 mm.



(a) (b)

Figure 4 (a) VARTM setup for the molding of a C-shaped laminate. (b) Definition of spring-in angles at resin ($\Delta\theta_{RES}$) and vacuum ($\Delta\theta_{VAC}$) side, and web warpage (w).

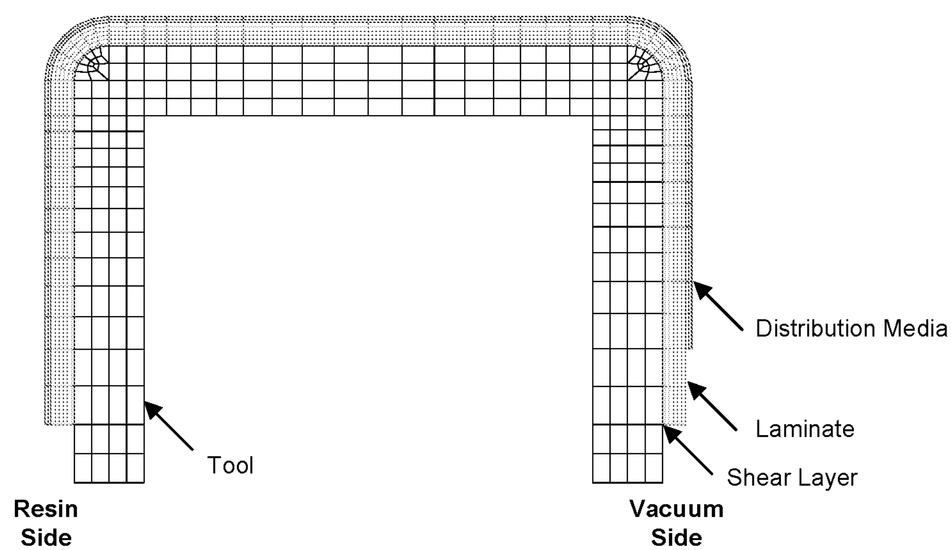


Figure 5 Finite element mesh used to simulate the C-shaped laminate cure in COMPRO.

Table 1 Results from simulations.

Case	Distribution Media	Flow	Initial V_f	$\Delta\theta_{RES}$ (°)	$\Delta\theta_{VAC}$ (°)	w (mm)
1	No	no	0.45	1.07	1.07	0.057
2	No	no	0.55	0.87	0.87	0.056
3	No	yes	0.45	1.02	0.97	0.053
4	No	yes	0.55	0.87	0.86	0.053
5	Yes	no	0.45	1.10	1.10	-0.090
6	Yes	no	0.55	0.90	0.90	-0.070
7	Yes	yes	0.45	1.06	1.01	-0.070
8	Yes	yes	0.55	0.89	0.87	-0.084

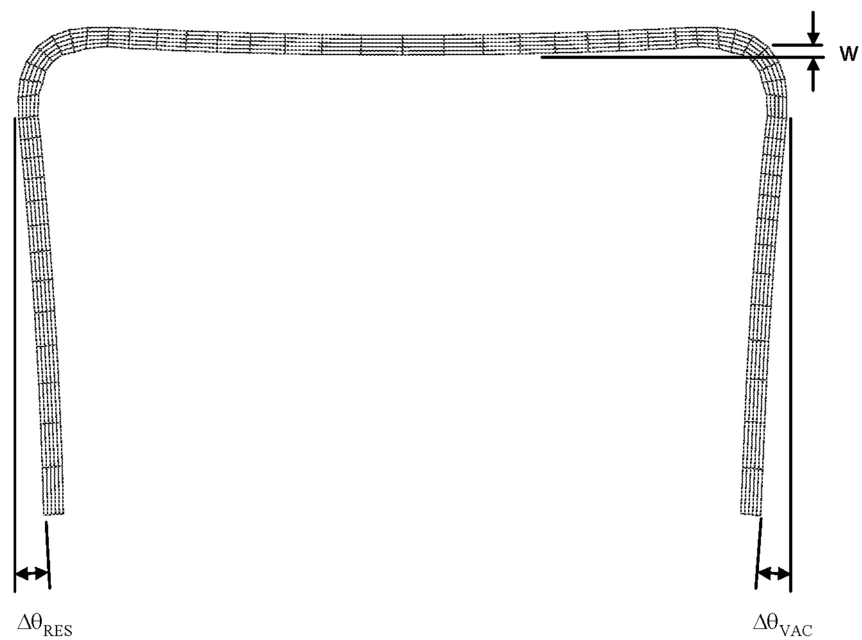


Figure 6 Deformed mesh showing the C-shaped laminate spring-in and warpage after cure.

Figure 7 shows a typical fiber volume fraction distribution obtained when flow boundary conditions were applied. The resin side has a lower fiber volume fraction compared to the vacuum side. This phenomenon is typical of the VARTM process, since the laminate thickness is controlled by the local resin pressure and fiber pressure

distribution. Thickness control for VARTM is a critical problem that was addressed by Gama et al. (ref. 13). These results presented here suggest that this thickness variation and consequently the fiber volume fraction variation can significantly influence the part distortion. For the present study, a difference of 6% in fiber volume fraction can lead to a difference of 0.05 (≈5%) in spring-in angle. This difference could cause assembly problems for components that require very tight tolerances. The difference in spring-in angle is more likely caused by different composite CTE at the corner, since the CTE is a function of the fiber volume fraction. This also explains the lower spring-in angle obtained for high fiber volume fraction (V_f=0.55) compared to low fiber volume fraction (V_f=0.45). It is well known that the magnitude of the angle spring-in is largely a function of the difference in in-plane and out-of-plane CTE at the corner. Variation in fiber volume fraction will mostly affect the out-of-plane CTE and thus a more resin rich laminate will typically have higher spring-in.

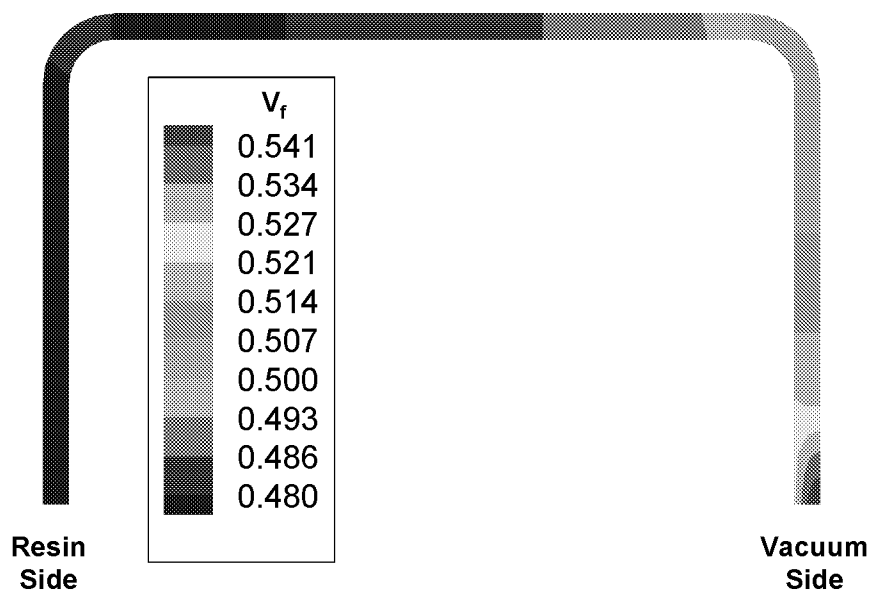


Figure 7 Fibre volume fraction (V_f) distribution induced during infiltration.

The presence of the distribution media during cure was found to affect the residual stresses in the laminate. Figure 8 shows the longitudinal stresses, in the material direction (σ_1), in the laminate before tool removal for the case when the distribution

media was not included in the simulation. Figure 9 shows the σ_1 stress distribution before tool removal when the distribution media was included. In both cases, tensile stresses can be observed inside the corners, while compressive stresses are present outside the corners. This stress distribution will result in the spring-in of the webs when the tool is removed. The difference in the stress distribution between Figure 8 and 9 is mainly in the longer region with compressive stresses just under the distribution media. This will result in a slightly greater warpage and consequently in a higher spring-in angle for the case with distribution media. From Table 1, it is important to notice that the presence of the distribution media affects the sign of the web warpage from positive (no media) to negative (with media). These compressive stresses are attributed to a combination of high cure shrinkage and CTE of the resin rich distribution media compared to the laminate. Although, the magnitude of the effect of the distribution media is small for this case, thinner gauge laminates will be more significantly affected by this phenomenon. Again, for more accurate prediction and process control, the distribution media has to be included in the simulation of composite laminates processed by VARTM.

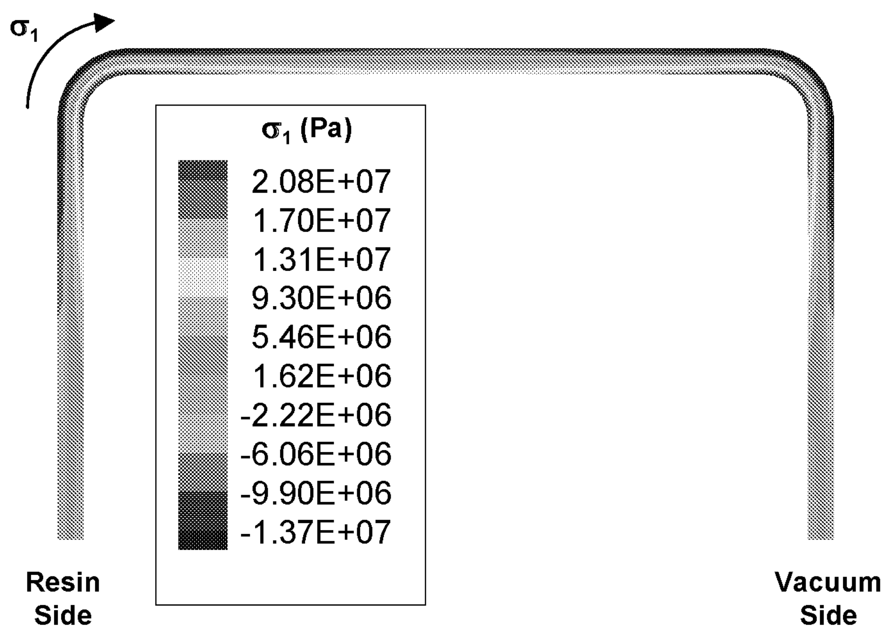


Figure 8 Longitudinal material stress (σ_1) distribution at the end of cure before tool removal for the C-shaped laminate neglecting the distribution media.

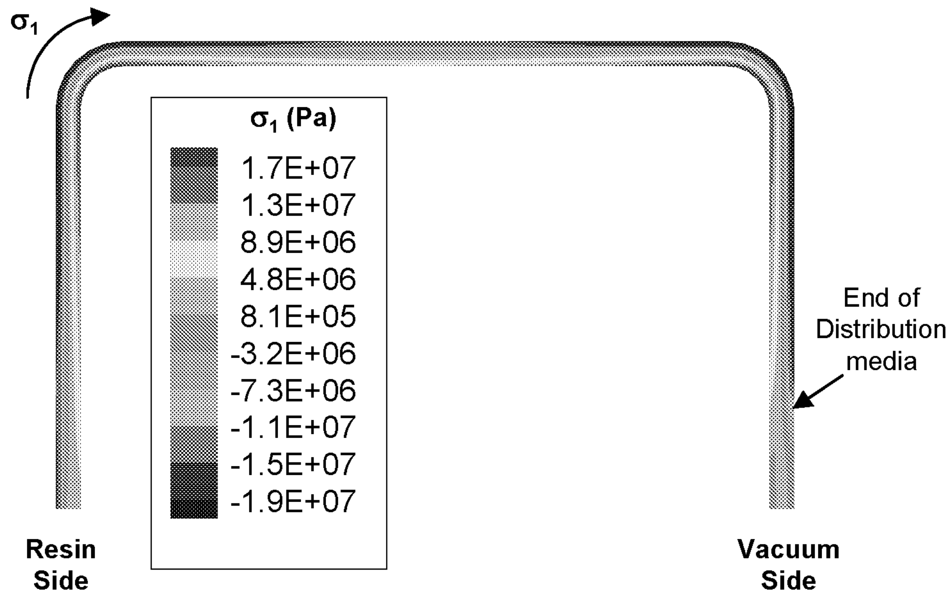


Figure 9 Longitudinal material stress (σ_1) distribution at the end of cure before tool removal for the C-shaped laminate including the distribution media.

CONCLUSIONS

The composite processing model COMPRO© was utilized to study the influence of the distribution media used in VARTM on internal part temperature distribution and part distortion. It was found that the presence of the distribution media could increase the exothermic temperature by 16.4 C for a 28 mm panel. The analysis of the distortion of C-shaped laminates showed that the spring-in angle and web warpage are affected by the local fiber volume fraction and that the presence of the distribution media alters the residual stress distribution in the laminate.

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